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The effect of building envelope on the thermal comfort and energy saving for high-rise buildings in hot–humid climate

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ABSTRACT

This paper is about the research into the effect of building envelopes on energy consumption and thermal performance of high-rise buildings in the Malaysian Tropical climate. A suitable indoor thermal condition in buildings is important because of the building occupants comfort. In addition, it is indicating building energy consumption, staff productivity, less absenteeism, health and well-being effects. Energy consumption can be significantly reduced by adopting energy efficiency strategies in such buildings. Due to environmental concerns and expensive energy costs in recent years, energy efficiency in buildings has garnered renewed interests. A research recently conducted in Malaysia specifies that residential buildings do about 19% of the overall energy consumed in Malaysian sectors. One of the most potential strategies applied on building envelope in hot–humid tropical regions is the passive design method and is done to the building envelope in hot–humid tropical regions. This paper reviews the results of the other studies that establish to the selecting of proper parameters of building envelope to the high-rise residential. The building design criteria has been scrutinized through a set of defined parameters such as climatic conditions, form, width, length and height, external walls, roofs, glazing area, natural ventilation and occupants thermal comfort, as well as external shading devices on energy consumption of high-rise buildings in Malaysia. The thermal comfort zone was investigated by researchers for Malaysian residential buildings, discovering that the comfort ranged between 25 °C and 31 °C. Recommendations are given based on the significant findings as resources to help designers in laying out the design plan for high-rise buildings in hot and humid climate.

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1. Introduction

Due to the rate of economic development and growing population densities in the South East Asia countries, majority of these cities are dominated by high-rise apartment buildings [1]. Improvement of building services and comfort level and growth in population have increased building energy consumption to the level of transport and industry [2]. The research undertaken by Ref. [3] specified that 40% of world energy are being consumed by buildings. The massive magnitude of energy consumption in buildings for cooling and heating by heaters and air-conditioner systems portrays a huge problem to the system. Available Statistics states that the Heat, Ventilation and Air Conditioning (HVAC) systems in standard buildings accounts for more than 50% of annual energy consumption globally [4]. This, coupled with the threat of increasing global temperature and energy cost, induce the need to regulate the temperatures in this buildings [5].

Different countries building sector had adopted the reduction of energy requirement and mitigation of environmental impacts as a key target energy policy, this being paired by strategies designed to strengthen renewable energy and energy efficiency technologies [6]. Based on the potential to invert the actual trend of energy consumption energy efficiency implementation measures in buildings has been prioritized [7]. A study in Malaysia indicates that about 19% of the total energy consumed by all sectors in Malaysia are from Malaysian residential buildings [8]. This amount increases steeply whilst occupants use air-conditioning systems for achieving better thermal condition especially during the hot months which increases energy consumption [1].

According to these challenges, attempts are done in different scales to reduce cooling and heating load in whole of the world. Under design and construction zone, bioclimatic design, utilizing renewable energy and passive design strategies like smart design of building envelope have been considered as the main solution for the decrease of environmental load by scholars recently. However, current study reviews literature on potential of building envelope on energy saving and comfort achievement for high-rise buildings in tropical climate. This is done to understand how building envelope components influence on building thermal performance.

The intensity of environmental forces differ according to climate zones and particular site conditions [9]. In Malaysia, the constant exposure of solar radiation towards building surfaces causes the increase in the amount of energy which is needed for cooling purposes. These surfaces must be protected to reduce the inflow of heat, directly or indirectly. All strategies to avoid building from solar radiation can be included into heat avoidance techniques. Appropriate shading especially for apertures, building orientation, vegetation surrounding building and relevant materials for façade is some intelligent strategies to prepare comfortable indoor temperature. These strategies are applicable in different climate and they are suggested for tropical climate where high amount of solar radiation is not preventable [10]. Shading devices are considered as relevant building façade elements because they protect glazed windows penetration of incoming heat which leads to the risk of overheating [11,12]. Therefore, it is vital to consider using various design configurations and assemblies of building envelope to address this situation.

The building envelope is divided into opaque and transparent elements [13]. It is constructed to protect the building from harsh environmental conditions while providing thermal comfort. Using a poorly designed building envelope will cause higher consumption besides relinquishing thermal comfort. Simply stated, the design of building envelope affects energy consumption. Building envelopes reduces energy consumption by protecting the interior from direct solar radiation penetration while reducing glare, minimizing water penetration, providing natural ventilation, reducing external reflection, providing view and acting as a thermal barrier.

The range of thermal comfort can be determined with regards to outside climate conditions, ethnic factors and adaptive behavior of occupants. These factors have been thoroughly described in different building standards [13]. American Society of Heating Refrigerating and Air Conditioning Engineers (ASHRAE) Standard 55 and ISO Standard 7730 define thermal comfort as the condition of mind which expresses satisfaction with the thermal environment [14,15]. In other words, it describes a person's psychological state of mind with regards to the weather; whether it is too cold or too hot [5]. When the majority of people reached the range of climatic conditions where they are comfortable with the heat or cold, they have reached the comfort zone.

Humans strive to create a thermally comfortable environment. This can be seen in building traditions around the world since ancient history. Currently, it is still one of the most important considerations when designing modern buildings [13]. The cooling, heating, lighting and ventilation systems exist in responds to the growing needs of building occupants. Sufficient daylighting as source of lighting that it provide more comfortable and satisfying in indoor environment [16] . It has been recognized that good daylighting decreases requirement on electrical lighting [17]. The design of a building thus affects the conditions of how these needs and desires are met. More than that, choosing the correct design affects how much non-renewable energy resources is needed to provide such services [9].

2. Tropical climate

The performance of a building can be significantly affected by climate. The significant of a 'design with climate' approach was highlighted by the study of Ref. [18], this study highlighted the impact climate conditions can have on design decisions. The effect of the overall energy performances of the building is aimed at the architectural and technical solutions that impact on performance.

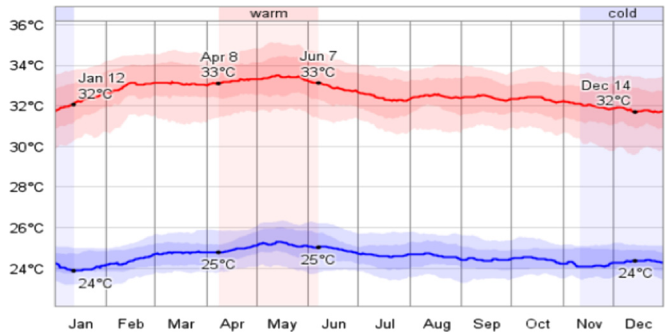

Fig. 1. Daily high and low temperature (Weatherspark, 2013).

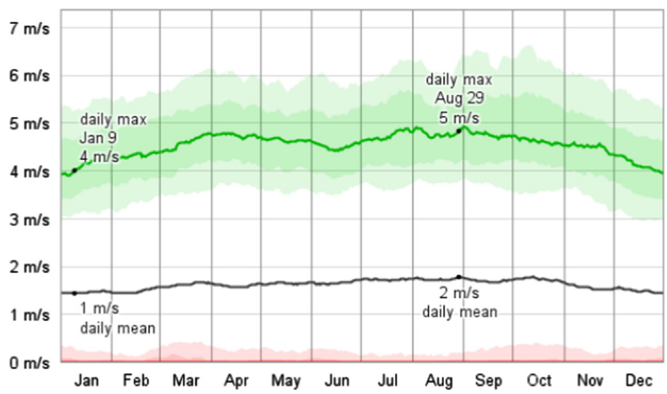

Fig. 2. Wind speed (the wind is most soften out the North West (17% of the time), North (14% of the time), South (12% of the time) and West (11% of the time).

The thermo physical properties of a building envelope are crucial due to its effect on indoor thermal comfort and energy conservation [19]. In the architectural sense, it is most difficult to enhance these properties through design due to the high humidity and daytime temperatures which result in high indoor temperatures; which exceeds the ASHRAE summertime comfort upper limit of 26 °C throughout the [20,21].

The geographical location of Malaysia is at latitude 3.12 °N and longitude 101.55 °E. The country experiences high humidity and temperature throughout the year. Buildings located in tropical regions like Malaysia face to typical hot and humid climate, little seasonal variation with a constant annual average. The climate is hot and humid all year around with uniform temperature and high humidity. Report describes the typical weather at the Sultan Abdul Aziz Shah Airport (Subang Jaya, Malaysia) weather station over the course of an average year.

The weather condition is such that it is a rear circumstance to witness days completely without sunshine except during the northeast monsoon season and unusual to witness a whole day with a clear sky in drought season 2013 is presented in Fig. 1; in which there are uniform temperatures throughout the year 2013. Furthermore, data in Fig. 2 shows that the overall wind condition through the year is calm and there is a need for increase of air speed in building. Study by Refs. [22,23] prove that there is a need to improve air speed on the skin surface to enhance thermal comfort in tropical buildings by using passive design elements and techniques.

3. Thermal comfort studies in Malaysia

Large numbers of surveys have been carried out by researchers in Malaysia to determine the comfort range and most of these studies are based on either climatic chamber or field studies. The study of multi-stories residences enabled the introduction of different comfort range of residential buildings in the system. The research findings from the studies for the comfort range of natural ventilated dwellings are shown in Table 1.

Table 1
Findings from thermal comfort studies carried out in Malaysia.

Researchers	Neutrality value/ Tn C	Indoor design condition		
		Comfort range (°C)	RH%	Air velocity (m/s)
[24]	30 C° regardless of the adopted methods	N/A	N/A	N/A
[25,26]	26.4 °C	Between 25.3 °C and 28.2 °C by 90% satisfaction	N/A	N/A
[27]	28.2 °C	25.0–31.4 °C	45–90%	N/A
[28,29',30]	26.2 °C for both mixed mode and air-conditioned buildings, and 25.5 °C for the climate controlled buildings	N/A	50% RH and no air movement	N/A

3.1. Adaptive thermal comfort concept

According to Hensen, thermal comfort is defined as a state where no driving impulses exist so as to modify the environments by the behavior [31]. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) define thermal comfort as the mind condition in which satisfaction with the thermal environment is expressed [32]. Thus, it will be affected by personal differences in terms of mood, culture as well as other individual, social and organizational factors. According to the abovementioned definitions, comfort is a state of mind versus a state condition. As the condition of mind or satisfaction can vary, the definition of thermal comfort can also be diverse. However, it correctly stresses that the judgment of comfort is regarded as a cognitive process which involves several inputs affected by physical, psychological, physiological and other factors [33].

Usually, thermal discomfort is considered as a subjective condition, whereas thermal sensation is treated as an objective sensation [31]. The matter of satisfaction with the thermal environment can be a complex subjective response to a number of interacting as well as less tangible variables [34]. To put it in another way, it is argued that thermal comfort has no absolute standard. Generally speaking, comfort takes place when body temperatures are within narrow ranges, the moisture of skin is low, and the physiological exertion of regulation is diminished. Comfort is also dependent on behavioral actions like changing clothing, changing activity, altering posture or position, changing the thermostat setting, complaining, opening a window, or leaving a space [35]. Macpherson, in 1962, defined six factors as those influencing thermal sensation including four physical variables (such as air temperature, relative humidity, air velocity and mean radiant temperature), along with personal variables (like clothing insulation and activity level, that is metabolic rate) [33]. Normally, thermal comfort standards try to determine the energy consumption via buildings' environmental systems; thus, they play a crucial role in creating sustainability [36]. This kind of energy often entails the use of fossil fuels, which contributes to carbon dioxide emissions as well as climate change [37]. Further, thermal comfort is regarded as a key parameter for a productive and healthy workplace [38,39].

4. Building envelope components in architecture

The function of building envelope is to physically separate the interior of the building from the exterior environments. Therefore, it serves as an external protection to the indoor environment while facilitating as climate control at the same time [5,40,41]. Environmental control installations must be taken into account in relation to the external conditions [5]. Because of the fact that building envelopes separate the indoor from outdoor environments, they are exposed to temperature fluctuations, humidity, air movement, rain, solar radiation and other natural factors [42]. Climatic thermal design of the building envelope affects thermal performance which also affects energy consumption [43]. In order to reduce the cooling energy consumption in the hot humid area, it is important to limit the amount of heat gain using the building envelope [5,44]. Generally, there are two main building envelope systems; namely the opaque and the transparent system. Opaque envelope systems includes walls, roofs, floors and insulation while transparent envelope systems include windows, skylights, and glass doors as shown in Fig. 3 [5,45].

The opaque envelope surface take in ample solar irradiation throughout the year in the tropical region [5]. Chua and Chou [46] undertook a computational simulation within a high-rise (12-storey), residential air-conditioned apartment buildings in Singapore. They found that heat gains over the opaque envelope surface contain of about 30% (along with about 11% through roof and 19% through walls) of the overall power consumption for the air-condition in the building [46,47].

There are five methods in which heat and mass transfer in the buildings:

- Conduction through opaque elements including external walls, ceiling, floor slabs, roofs and partitions.
- Solar radiation and conduction through window glazing.
- Infiltration of outdoor air and air from adjacent rooms.
- Heat and moisture dissipation from the lighting, equipment, occupants and others materials inside the room.
- Heating or cooling and humidification or dehumidification provided by the HVAC system [13].

A study by Ref. [48] shows that 73% of the total heat/gain loss is contributed by the building envelope. The choice of construction materials is dependent on the thermal, moisture and sound considerations. Walls, doors, windows, ventilators, roofs, etc are components which are directly exposed to the sun [5].

More studies are required on envelope behavior especially in residential buildings due to the adaptive behaviors, natural ventilation, non-conditioned spaces and various occupation schedules. Even though new solutions are crucial in design stage, it is also vital to understand primitive passive cooling strategies that help in residential designs. The evaluation of the performance of the building envelope is a first step towards building stabilization and habitation.

4.1. Ventilation cooling through building envelope components

The study conducted by Ref. [49] portrays that adopting the natural ventilation system in a building environment lowers energy consumption and green gasses emissions. Subsequently, it advances the rate of thermal comfort in indoor and the usage of fresh air in buildings shows that greater occupant control along with high levels of environmental quality may be achieved compared to mechanical ventilation by using natural ventilation in the design of residential buildings [50]. The advantages of natural ventilation include reduction of operation costs, preparation of satisfactory thermal comfort as well as modification of indoor air quality. The use of natural ventilation as an inactive and passive cooling strategy for buildings provides a significant opportunity to address issues associated with artificial cooling buildings [51].

The usage of natural ventilation in buildings dates back to the creation of some architectural components in traditional buildings prior to the application of active systems like air-conditioning. Some of these kinds of elements are still utilized in modern buildings. The building façade such as walls, roof as well as all openings like windows play important role in controlling air flow, and they help make sure the indoor air could be maintained via a combination of fresh outdoor air with indoor air. Definitely, the proper façade design can reduce the overall cooling load and decrease the use of air-conditioning [52]. Typically, double skin façade is regarded as one of effective strategies useful for the design of façade that reduces transmission via protecting reflective glass walls [53]. A proper design and adequate location of the opening together with the appropriate number of windows and doors can be the key factors to create the necessary wind for thermal comfort [54]. Literature evidences that single side ventilation and night ventilation may reduce the cooling requirements by 30% provided that the apertures are situated in related parts of windward sides [55]. A relevant study by Ref. [56] revealed that a combination of these design strategies will decrease cooling needs over 40% per unit.

Correspondingly, a study by Ref. [57] presented some variables for the construction like building mass, solar and internal gains, glazing ratio and orientation, and show that the building design optimization for night ventilation based on these parameters may

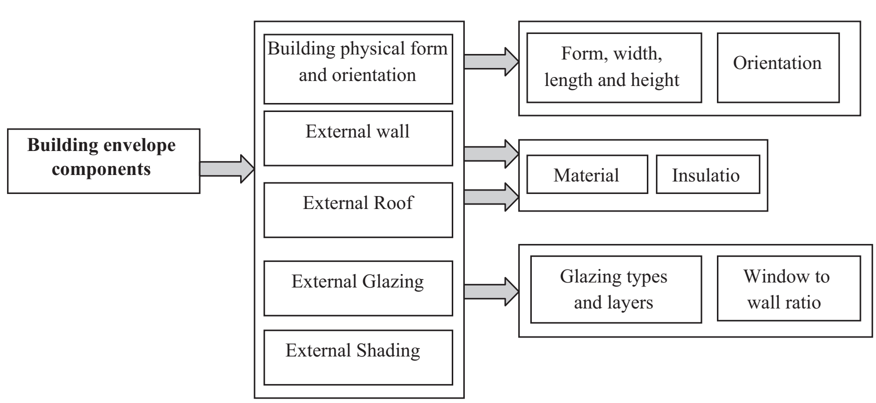

Fig. 3. Building envelope components in architecture.

cause a reduction of around 20–25% of consumption of the air conditioning energy [58].

There are several buildings established by using either design elements or guidelines via building facade to improve thermal comfort by the use of natural ventilation. A relevant research on the application of natural ventilation design for house was conducted in Thailand to evaluate air-rate and size of apertures in a particular climate in order to obtain thermal comfort. Accordingly, thermal comfort and climate analysis were carried out using CFD simulation model to find out optimum site planning as well as design in tropical climates. The study result reveals that an indoor air velocity of 0.4 m/s could enhance indoor thermal comfort. Besides, it shows that the total area related to inlet and outlet apertures has to be 40% of the whole floor area approximately [59]. A study on the use of natural ventilation in buildings with high density was conducted to propose and develop an ideal model for decreasing environmental load. CFD simulation and field experiment were used to evaluate the decrease of CO_2 emission by the usage of natural ventilation in diverse design models. The study results revealed that by natural ventilation, the CO_2 emission can be reduced by 30%. In addition, the life cycle building can be improved by 22% with natural ventilation by using ideal porous-design models [60].

A related study by Ref. [61] on tropical climate showed that stack effect regarded as one of the strategies for producing ventilation is inadequate due to lower range of air temperature (i.e., less than 5 °C) between outside and inside of building. Nevertheless, high amount of solar radiations may be taken as a viable alternative to make ventilation in tropical climates. Therefore, solar induce ventilation offered in the past studies may achieve adequate ventilation inside buildings. Accordingly, metallic solar and solar induce ventilation were tested by Ref. [62] in Thailand in order to eliminate heat from indoor spaces. The study reported that the MSW which has 14.5 cm air gap with 2 m^2 of surface area ($H \times W$: 2 m × 1 m) resulted in the highest air mass flow rate of around 0.01–0.02 kg s^{-1}. Based on the results obtained from solar wall, a study by Ref. [63] used different shapes of roof solar collector to gain more ventilation. Among the diverse shapes of roofs, the suitable range of tilt angle ought to be considered from 20° to 60°. The study results revealed that for $\theta > 60°$ the air flow rate increased, but insignificantly. A relevant study demonstrated that the use of roof solar collector in combination with metallic solar wall and trombe wall at a public building decreased overheating by around 50% [64]. Based on other researchers, solar induced ventilation technique can be used with other passive cooling strategies to increase air velocity. Chungloo and Limmeechokchai [65] studied roof solar collector with wetted ceiling to reduce indoor air temperature. The studies revealed that when the roof solar collector was used independently, the room temperature was reduced by around 1–3.5 °C. However, the combination of both strategies reduced the room temperature between 2 °C and 6.2 °C.

However, while previous studies that examined roof solar collector efficiency reported that its inclination shape has been able to absorb more solar radiations compared to perpendicular and vertical solar induced ventilation systems like trombe wall. The roof slope, which affects stack height is still a challenge and studies are yet to be undertaken on this issue [66].

4.2. Building physical form and orientation of high-rise residential building

4.2.1. Building form, width, length and height

The pattern a Building adopts can notably affect the effectiveness of its apathetic cooling strategies. Numerous studies did observe the efficiency of the various building strategies in reducing solar radiation [46]. Hyde's research on climate responsive design for buildings, used strategies such as the roof designs and permeable wall, the application of shade verandahs, courtyards and plan orientation to assess passive design notion and how they affect the thermal comfort. His study confirmed that plan dimensions greater than 15 m decrease the effectiveness of natural ventilation and as a result the degree of thermal comfort [67]. Most building designers can come out with the basic plan, shape and materials of the building without considering the climatic influence. Due to the building orientation on site and its exposure to solar radiation, its shape can influence the energy consumption of building. Other factors that are influence by building shape are day lighting and air movement [5]. There are some researchers that have considered high-rise building shapes in their research and its response to climate [68]. Most studies attested that, whilst maintaining an overall densities lowers the site coverage, an increased building height improve outdoor ventilation [46,69,70]. Kannan [45] suggests that there is no definite conclusions in terms of the association between building height and energy consumption [9,45]. However, plan ratio and shape are found to be directly influenced by the building form. Therefore, in an energy and environmental aspects, floor plate depth can be determined by the width to depth ratio factor [68]. The optimum building forms for each climatic zone were given as ratio of the length and the width of the building. The acceptable shape that can be applied in the hot and humid region falls in the ratio ranged between 1:1.7 and 1:3, where 1:1.7 was considered the optimum shape that can be applied [71].

Several methods have also been used to determine the height of the high rise buildings [72] that were developed for wind flow studies. The height of high-rise buildings in Malaysia ranges between 5 and 88 stories. The longitudinal façade is preferred to face north and south. However, this does not necessarily help alleviate energy consumption [9,73]. Kannan states that buildings lined longitudinally along north and south had 10% less energy consumption than building arranged longitudinally along east to west, regardless of building form [45].

4.2.2. Building orientation

The design plan to employ the wind induced ventilation in a multi-story apartment buildings for hot humid climate was initiated by Givoni, which propose that the building's direction needs to be oblique to the prevailing wind [74,75]. A research by Ref. [9] in Malaysia suggested that when compared by day-to-day, thermal performance orientation have a significant impact amid the presence or absence of natural ventilation. By avoiding the east and west windows siding closely results in a more acceptable indoor environment. Additionally, a 16% upgrading in the indoor thermal hours per annum could be achieved if the un-ventilated room oriented to the north compared to the Base Case oriented to the south–west. Yearly the west and south–west are worst off in terms of the total hours less than 28.6 °C in a ventilated and non-ventilated rooms all through night-time. On the other hand, the east and south–east are worst off orientation during day-time period regardless the ventilation condition [9]. North orientation is considered as the most select design practice on residential buildings in Malaysia [9].

4.3. External wall

Walls are important parts of a building envelope as they give thermal and acoustic comfort without compromising the aesthetics of the building. Wall design potentially allows passive control of indoor conditions within the building through the management of external outdoor temperature transfer [5]. To ensure stability of temperature and relative humidity in a building despite fluctuating exterior conditions, buildings today are required to have a high degree of thermal inertia [76].

The study by Ref. [77] focus on the impact of using cool paints and/or thermal insulation on the thermal behavior and energy demand of a residential building. Based on the results, it was found that an increase in roof and façade value of Total Solar Reflectance (TSR) from 50% to 92% reduced the maximum indoor free-float temperature between 2.0 °C and 4.7 °C in old construction (without thermal insulation), and between 1.2 °C and 3.0 °C in new construction (with thermal insulation). This had as a trade-off effect the decrease of the minimum indoor temperature of up to 1.5 °C. The results of annual energy demand for heating showed a maximum penalty of about 30% when using cool paints.

The thermal properties of a material will determine its ability to absorb or emit long wave solar radiation. In addition, it also influence the insulation properties of the material particularly the *U*-value. Applying insulation material within the building also affects its performance during transient heat flow.

4.3.1. External wall materials

When considering construction materials, there are two main categories, namely the high thermal mass and low thermal mass. The first category of materials with high thermal mass are cement blocks, bricks and other solid masonry materials. These materials absorb heat from solar radiation at a slower rate and are very effective in countering rapid heat transfer. The second category includes materials with low thermal mass are timber and steel. These materials absorb heat quickly but release it quickly as well. According to the literature review, there are many different tropical design factors for wall [78]. Lightweight construction responds quickly to cool breezes, high mass construction slowly releases heat that is absorbed during the day. In high humid climates, high mass construction is not recommended because of their limited diurnal range. However, low mass buildings are preferred due to their effectiveness in passive cooling [5]. While low mass construction is the optimal choice, recent research showed that innovative, well insulated and shaded thermal mass designs can lower night time temperatures by 3–4 °C in high humid areas with modest diurnal ranges [5].

A study conducted in Thailand on the economic performance of thermally light and massive walls from an experiment and simulation revealed that thermally massive walls delay heat transfer into internal spaces. It also delay the rise in internal surface temperatures. These factors decreases the air-conditioning load, which is only used in the daytime. However, this phenomena presents disadvantage for spaces that are used during night time. The study also concluded that thermally massive walls are not economical in the tropics [79]. Thus, for tropical regions such as Malaysia, low mass construction is preferred for saving energy and maintaining thermal comfort for its occupants.

4.3.2. Walls with thermal insulation

The building wall is crucial in determining the energy consumption of building due to its thermal resistance (*R*-value) capability. Thermal insulation is affected by the center-of-cavity *R*-values and clear wall *R*-values [42]. Appropriate application of thermal insulation in the building envelope is the most effective method to reduce the rate of heat transmission and energy consumption for the cooling and heating of the internal space [80]. When buildings are properly thermally insulated, the annual cooling load and peak cooling demands for buildings in hot dry and hot humid regions can be significantly reduced [76]. With thermal insulation, walls have higher tendency of surface condensation when the relative humidity of the ambient air is higher than 80%.

The thickness of insulation material used is one of the most important aspects in building design because thick insulation material means less internal space [81]. Typically, about 25–30 mm of insulation material is used in a 50 cm-thick wall to comply with the building codes and regulations practiced in different countries [42]. Orthodoxly, walls are classified into wood-based walls, metal-based walls and masonry-based walls according to the materials used for their construction. Other types of advanced building wall designs are also available to improve energy efficiency and building comfort levels.

4.4. External roof

Roofs determine the indoor conditions of buildings, thereby affecting the conditions for occupants due to its exposure to solar radiation as well as other environmental factors. Normally, composite roofing systems are preferred to produce the required roof specifications based on the weather conditions and location in which the building is situated. In countries with high intensity of incidence sun radiation, roof construction is even more crucial. Some passive cooling techniques could be implemented in tropical climates as result of modification in roof architecture [42]. More attention is needed especially in tropical countries like Malaysia where the global radiant temperature is high. To handle this situation, insulation is used due to it being an inexpensive solution for solar heat transmittance. There are many types of roof insulation materials like the reflective (such as aluminum foil) types, which have low thermal emittance; and resistive types (polyurethane) insulation [13]. The popularity of the Cool roof system has swelled over time as a static building energy saving solution. To assess the impact of the cool coating on heat transfer and indoor thermal comfort a concise and easy-to-apply mathematical model is needed to build the designers and to this a novel cool roof heat transfer modeling (CRHT) was develop by adopting the spectral approximation methodology. Based on an experiment performed in two identically configured apartments with concrete roofs in Singapore the CRHT model was confirmed against the conduction transfer function method and was validated. The radiation component is affected by Cool coating as it provides high solar reflectance and high thermal emittance. A cool coating layer appends resistance to the heat conduction through the roof/wall, and is coupled with the surface heat exchanges in line with quantitatively analyzing the impact of cool coating on the roof/wall heat transfer phenomenon, a robust heat transfer model is crucial [47]. Innovative modifications can be done to improve the capability to handle high solar radiation. Examples include applying a compact cellular roof layout with reduced exposure to the sun, high roofs, double roofs, vaulted roofs or roofs with domes, ventilated and micro ventilated roofs [82]. Corrugated metal roofs are very common in most developing countries and also at night the low-mass roof cools down rather fast, acting in effect as an effective nocturnal radiator located directly above the living space. The indoor night settings is in such that the buildings are often more comfortable than in those with high-mass, and insulated roofs. However, through the daytime the indoor temperature in buildings with such roofs is often very uneasily hot, as un-insulated metal roofs exhibit much higher temperatures than a massive concrete roof [83]. In Malaysia, flat roofs are inadvisable because of possible leaking in times of heavy rain (Karim, 1988) as well as cracking due to contraction and expansion, regardless of whether the roofs are made of concrete with or without a false ceiling [84]. On the other hand, pitched or sloping roofs specially designed to withstand the frequent sudden tropical showers and violent winds are highly recommended. The heat conductive nature of metal roofs such as those made from aluminum, Zinc, copper, or stainless steel are unfavorable for heat reduction

Table 2
Maximum *U*-value for roof (W/m^2 K) [13].

Roof weight group	Maximum *U*-value (W/m^2 K)
Light (under 50 kg/m^2)	0.4
Weight (above 50 kg/m^2)	0.6

because it easily conduct heat and corrode when in contact with sculpture dioxide in the atmosphere [84]. The reflectance of a surface (usually expressed as ratio of the reflected energy to the total incident radiation energy) quantifies the energy that is neither absorbed nor transmitted [85]. Agrawal (1974) suggested that light colored roof may contribute in the deflection of unwanted summer heat, thus reducing heat transmission into the building. In a general term, the means by which the temperature inside a dwelling is lowered to about 3 °C is through the utilization of a light color bulb and also insulation include an additional decrease of 3 °C. The preserved thermal power is 150 W per m^2 of the protected area, and the evaded thermal energy is equal to 250 kWh/m^2 for the wet season period [86]. In green building index for none residential buildings with air conditioned below space, maximum recommended roof thermal transfer value (RTTV) is 25 W/m^2; this has been established based on maximum *U*-value proposed by green building index for none residential buildings of Malaysia (Table 2) [13].

4.5. External glazing

4.5.1. Types glazing and layers

Windows are one of the most important components in the contribution of energy loads [5]. Besides that, it plays a dominant role in the building's exterior aesthetics [87]. Significant amounts of research works were conducted to comprehend the effect of different glazing types on energy consumption. Moreover, studies were carried out to establish a system for energy labeling and energy rating of windows when compared to a standard window [88–93]. According to Refs. [9,94], the most commonly used types of glazing are:

- clear glass
- heat absorbing glass
- heat reflecting glass
- low-emissivity glass
- super insulating glass
- gray and colored glass

In addition, the transmittance of the glass profoundly affects the efficiency of daylight which induced energy savings. When glazing transmittance is reduced, lighting energy savings is also reduced. Tinted windows help in energy savings and are linearly dependent on window area, which is dissimilar to the diminishing returns behavior of higher transmittance glazing [95].

When designing windows the amount of glazing layers and the glazing type are included in the crucial factors the designer should consider. This could impact equally the quantity of light transmitted into the built space and the magnitude of solar heat gain, which therefore cause an increase in the cooling load [96].

Gut and Ackerknecht [97] recommended that windows in tropical climates should be large and can be fully opened, with identical inlets on opposite walls for cross-ventilation [5,97]. Thermal performance of windows fundamentally hinges on its *U*-value which represents the heat loss coefficient. In other words, the thermal performance improves when the *U*-value becomes lower, and this can be achieved in different climate conditions through different means such as adding more glazing layers, applying special coatings to control solar radiation, and avoiding gaps between two layers with low thermal conductive gases such as argon or krypton [87,98].

4.5.2. The window to wall ratio

The ratio of window to wall area determines the amount of incident solar radiation entering into the interior [5]. In order to choose the correct glazing, it is important to consider the external climate conditions and expected building's internal environment [9]. Till present, glazing materials have been extensively experimented and modified to cope with external climatic effects of solar radiation, solar heat transfer and daylight transmittance [9,89,91,99].

According to a study, ventilation and indoor thermal comfort environment can be dramatically enhanced by 13% with the increase of window to wall ratio (WWR) size from 12% to 24%. Nevertheless, this also increases solar heat gain [100]. Eskin and Türkmen (2008) compared the yearly energy requirements per floor area at four climates in Turkey through four different window to wall area ratios (20%, 40% (Base Case), 60% and 80%). From this study, it was found that energy requirement became higher when the glazed area increased. When the window area ratio increased to 40–80%, the reaction of the building changed and subsequently widened the gap between the energy requirements of individual building [5]. Liping et al. on the other hand, carried out a thorough evaluation using building simulation and indoor CFD simulation to critically and accurately predict the indoor thermal environment for naturally ventilated buildings in the hot-humid climate of Singapore [100]. The window size in this coupled simulation differed from WWR = 10% to WWR = 40% for all orientations. From the results, it was recommended that the optimum window to wall ratio in Singapore is 24%. This percentage was suggested based on the improvement achieved in the indoor thermal comfort [5]. In Malaysia, the most frequently used are 6 mm thick glass with *U*-value of 5.6 W/m^2 K, shading coefficient between 0.4 and 0.96, and visible transmittance from 20–80% [101].

4.6. External shading

Shading devices reduce direct sun penetration but allow daylight to enter the space. They are designed for a number of purposes such as to avoid overheating, to decrease cooling loads, to manage visual environment (i.e. glare, color, light, contrast, view towards and from the exterior) [102], to protect the openings from atmospheric agents, and to provide a “sculptured skin” of buildings [102,103]. Additionally, shading devices provides significant impact towards improving internal thermal conditions in both ventilated and unventilated [12]. However, this may reduce the potential for incoming daylight which in turn increases the use of artificial lighting. Solar shading are desirable to architects compared to reducing the window area. This situation may provide a substitute to the design character of the building. Although solar shading devices are used to primarily block direct sunlight, the solar heat gain and energy consumption increases shading devices [9]. The solution to the overheating problem is preferred compared to reducing the area, because doing the latter would reduce the amount of natural daylight into the building [104]. Solar shading has thus become an alternative not only because of its aesthetics. It is crucial to give it a lot of thought so that it provides positive impact towards energy efficiency [9].

The best proven method for radiation control is the use of external static sunshade because their geometry can be customized in accordance to the seasonal sun path. The efficiency for the radiation control can be easily gauged after producing the shading characteristics for the sunshade, i.e., by plotting shading mask diagram location, latitude, and orientation to produce an effective control device [5]. In 2007, Wong and Li scrutinized the effectiveness of window shading devices on cooling energy consumption for east and west windows in Singapore. Results from the study shows that 2.62–3.24% savings occurred in terms of energy cooling load by applying a simple 30 cm-deep horizontal shading device to the window. When the depth of the window shading device was 60 cm, 5.85–7.06% of the cooling load was saved. When this approached 90 cm, the corresponding cooling load gone down by 8.27–10.13% [12,105]. In Singapore, Wong Nyuk scrutinized the effects of shading devices on temperature [106]. The results showed a 0.61–0.88 °C decrease in temperature when horizontal shading devices were applied. Moreover, vertical shading device further decreased the temperature by 0.98 °C in another study by Yang and Hwang (1999), which was done to understand the impact of external shading on energy savings in a building located in Taiwan. The study by Yang and Hwang indicated that, with proper installation of external shading, an average 25% saving can be achieved towards direct air conditioning power consumption [5].

In Malaysia, the results of a study indicated that the longer shading leads to the greater savings in both annual load and peak load. A horizontal shading device of 30 cm-deep between 2.62% and 3.24% the energy cooling load can be saved 5.85–7.06% of the cooling load could be saved by applying the depth of the window shading device is 60 cm [107]. In a nutshell, published literature has shown a comprehensive understanding on the influence of shading devices on daylight quantity and distribution [5,108,109], impact on energy use [110], and impact on human comfort and perception [11,111].

Tzempelikos and other researchers reported that with their tandem use with appropriate glass types, shading devices can mean big energy savings when they are applied, enabling them to regulate the thermal effect of windows to a great extent [12,112,113]. Therefore, external shading devices should be encouraged as architectural elements to protect building envelopes and occupants from solar radiation in Malaysia. In 2007, Wong and Li studied the effectiveness of window shading devices on cooling energy consumption for east and west windows in Singapore. The study shows that 2.62–3.24% of the energy cooling load can be saved by applying a simple 30 cm-deep horizontal shading device to the window. When the depth of the window shading device is 60 cm, 5.85–7.06% of the cooling load could be saved.

5. Result and discussions

According to the previous sessions, there are different elements and techniques through the building facade, which influences indoor thermal comfort and energy consumption. The above mentioned studies show different implication of applied elements through hot and humid climate and present effective strategies implemented in buildings. Further investigation on those studies has been applied in this session to recommend further studies on interaction of elements and techniques for decline of energy consumption and consequently the increase of thermal comfort degree in built environment. It is assumed that the complimentary elements could be applied in future studies to evaluate the performance of buildings in tropical climate in terms of comfort acceptability and energy saving.

5.1. Influence of glazing type and shading device on energy savings

As we discussed in earlier sessions, there are many studies on application of glazing types in high-rise buildings. The selected study by Ref. [96] shows how the different types of glazing impacts on annual energy consumption in Malaysia. As it is shown in Table 3, four different glazing types have been investigated in this study. The table shows thermal and lighting characteristics of the four glazing types including the number of panes, the visible transmittance, and the shading coefficient (SC). The 6 mm single clear glass that includes an aluminum frame is the glazing type used in all apartment cases based on outcomes, the utmost savings in cooling energy would increase up to 19% through the substitution of a single clear glass with the double clear glass lower. The results of the study by Ref. [9] indicates that a total improvement of about 107% and 14% may possibly be attained if the double coated reflective glass is used instead of the single clear glass.

Apart from studies on glazing types of transparent surfaces in tropical buildings, shading element has been considered in many studies. Study by Ref. [9] concluded that the egg-crate devices are the best in reducing indoor air temperature as it avoid the solar radiation from varied sun angles. The improvement in the number of the hours less than 28.6 °C compared to base case was found to be 167% and 14% in un-ventilated and ventilated rooms. Further study on exterior shadings screening shows the entire glass surface area can reduce direct solar gain by a maximum of 80% [114]. Looking to these studies and prior studies in session [refer to previous sessions on glazing and shading (4.5.1, 4.6), there is no studies and literature on application of complementary concepts including shading devices and different type of glazing's in buildings. The study recommend further research on multiple application of these effective elements on building façade. It could be achieved by application of simulation programs to evaluate the interaction of different glazing type and shading devices simultaneously. The results may improve energy saving and indoor thermal comfort in tropical region.

5.2. Influence of wall thermal insulation, materials and roof insulation on energy savings

Different studies on thermal insulation of walls and roofs have been investigated in many studies in tropical climate. Furthermore, the wall materials is another significant elements which has been evaluated in previous literature. According to the literature, the study by Ref. [96] found that exterior wall thermal insulation provide a significant reduction in both annual cooling energy and peak cooling load up to 20% and 29%, respectively. In another study, the simulation results demonstrated that, for all apartment cases and thermal insulation thicknesses, cooling energy consumption and peak cooling load are significantly reduced when

Table 3
Glazing types and its characteristics [96].

Glazing type	No. of panes	Visible transmittance	Shading coefficient	Solar heat gain coefficient	*U*-value (W/m^2 K)
Single-glazed clear 6 mm	1	0.88	0.95	0.81	6.4
Single tinted 6 mm	1	0.65	0.73	0.62	6.0
Double-glazed clear 6/12/6 mm	2	0.78	0.81	0.70	2.74
Double glazed clear low-e 6/12/6 mm	2	0.74	0.65	0.56	1.78

Table 4
The effect of building envelope parameters on thermal comfort.

Parameters of building envelope	Thermal comfort
Orientation	North orientation is the optimum for residential buildings in Malaysia [9]
Building form, width, length and height	Plan dimensions greater than 15 m decrease the effectiveness of natural ventilation and as a result the degree of thermal comfort [67].
	The acceptable shape that can be applied in the hot and humid region falls in the ratio ranged between 1:1.7 and 1:3, where 1:1.7 was considered the optimum shape that can be applied [71].
	Low mass construction with well insulated and shaded thermal mass designs can lower night time temperatures by 3–4 °C in high humid [5].
External wall	Increase in roof and façade TSR value from 50% to 92% able to reduce the maximum indoor temperature between 2.0 °C and 4.7 °C in construction without thermal insulation, and between 1.2 °C and 3.0 °C in construction with thermal insulation Able to decrease the minimum of indoor temperature up to 1.5 °C [77].
	The temperature is lowered to about 3 °C is through the utilization of a light color bulb and insulation include an additional decrease of 3 °C [86].
External roof	Roof insulation materials such as radiant barries for different climate indicates that the lowest summer integrated percent reduction in ceiling heat transfer was 2.3% in the Building forms can considerably affect the effectiveness and efficiency of passive cooling strategies [115].
	The optimum window to wall ratio in Singapore (hot–humid climate) is 24%. The 6 mm single clear glass that includes an aluminum frame is the glazing type used in all apartment cases. Total improvement of about 107% and 14% may possibly be attained if the double coated reflective glass is used instead of the single clear glass [9].
	Ventilation and indoor thermal comfort environment can be enhanced by 13% with the increase of WWR size from 12% to 24% [100].
	Total improvement of about 107% and 14% may possibly be attained if the double coated reflective glass is used instead of the single clear glass [9].
	Horizontal shading devices can able to decrease the temperature between 0.61 °C to 0.88 °C Vertical shading device can able to decreased the temperature by 0.98 °C [5].
External shading device	Total improvement of about 107% and 14% may possibly be attained if the double coated reflective glass is used instead of the single clear glass [9]
	Exterior shadings screening shows the entire glass surface area can reduce direct solar gain by a maximum of 80% [114].

Table 5
The effect of building envelope parameters on energy saving.

Parameters of building envelope	Energy saving
Orientation	Buildings lined longitudinally along north and south had 10% less energy consumption than building arranged longitudinally along east to west, regardless of building form [45].
External wall	Exterior wall thermal insulation reduce in both annual cooling energy and peak cooling load up to 20% and 29%, respectively [96].
	The exterior wall thermal insulation provide a significant reduction in both annual cooling energy and peak cooling load up to 20% and 29%, respectively [93].
	The cooling energy consumption is considerably minimized when 25 mm of (EPS) is applied on the inside surface of exterior wall by 14% to 14.5% for all cases [96]
External roof	The preserved thermal power is 150 W per m^2 of the protected area, and the evaded thermal energy is equal to 250 kWh/m^2 for the wet season period [86].
	The decrease was between 1.5% and 1.7% in yearly energy consumption, between 2.0% and 2.6% in yearly space conditioning energy usage, and from 12.3% to 13.6% in peak cooling loads [115].
Glazing	In Malaysia, the most frequently used are 6 mm thick glass with U-value of 5.6 W/m^2 K, shading coefficient between 0.4 and 0.96, and visible transmittance from 20% to 80% [101].
	The savings in cooling energy would increase up to 19% through the using of a single clear glass with the double clear glass lower [9].
	The necessary energy for cooling increases to 12.8% as the windows to floor ratio rises by 10.4% [1].
External shading	The depth of the window shading device was 30 cm, 2.62–3.24% savings occurred in terms of energy cooling load [12,105].
	The depth of the window shading device was 60 cm, 5.85–7.06% of the cooling load was saved [12,105].
	The depth of shading device was 90 cm, the corresponding cooling load gone down by 8.27–10.13% [12,105].
	The impact of external shading on energy savings in a building located in Taiwan with proper installation of external shading, an average 25% saving can be achieved towards direct air conditioning power consumption [5].

thermal insulation is added to the exterior walls [96]. This reduction depends mainly on thermal insulation thickness. In another studies by Ref. [96] shows that cooling energy consumption is considerably minimized when 25 mm of (EPS) is applied on the inside surface of exterior wall by 14–14.5% for all cases.

Study on roof insulation materials such as radiant barries by Ref. [115] for different climate indicates that the performance of attic radiant barriers depends on the climate in which the building is located. The lowest summer integrated percent reduction in ceiling heat transfer was 2.3% in the building forms can considerably affect the effectiveness and efficiency of passive cooling strategies. Numerous studies have investigated the effectiveness of various building arrangements in decreasing solar increase related to insulation thickness. The yearly energy application and peak cooling loads appeared to be largely lower than the case with no exterior wall insulation; nevertheless, the effects were found to be minor. The decrease was between 1.5% and 1.7% in yearly energy consumption, between 2.0% and 2.6% in yearly space conditioning energy usage, and from 12.3% to 13.6% in peak cooling loads.

Based on above discussed studies, the effective elements were examined in several studies in tropical region. Nevertheless, no study has been reported on application of such elements in a specific study investigating as a complementary concept. Hence, the arrangement of these elements in building façade may bring about novel and promising results for additional development of building. It is argued that simulation software may be the best option for evaluating these important elements in a specific building as a relevant case study. The present study suggest further researches on the use of wall materials as well as wall and roof insulation concurrently to obtain the optimum results for additional decrease in energy consumption of indoor spaces.

5.3. Influence of WWR and WFR on energy saving and thermal comfort

Studies have been reported on usage of window to wall ratio, window to floor ratio as well as their effect on comfort achievement. The focus of these studies is on the window size, as a main element in building façade, to explore the optimum size for aperture to receive sufficient light and ventilation without compromising thermal comfort of occupants. A relevant study by Ref. [9] reveals that the yearly thermal comfort hours raised with the decrease of WWR.

Regarding unventilated rooms, the thermal comfort hours rise steadily 2 °C were reported with every change in WWR by 10% in unventilated rooms and ventilated rooms, respectively. Another study by Cheung et al. [1] was conducted on the influence of WWR on building energy use by changing it from 0.1 to 0.4. It is observed that when WWR reduces 400%, the yearly energy consumption, the yearly space conditioning energy usage as well as the peak cooling loads are reduced 7.8%, 32.9% and 35.2%, respectively representing that WWR is an important contributor to the building energy usage and the peak cooling loads [116]. Window to floor ratio (WFR) was s in some studies in order to achieve the similar objectives as the ratio of window to wall area rule of thumb. The ratio of window area to floor area rule of thumb was frequently cited in building codes and literature of architecture [117]. A study by Ref. [1] showed that windows-to-floor ration directly affects the yearly required cooling energy. The study results indicate that the necessary energy for cooling increases to 12.8% as the windows to floor ratio rises by 10.4%. A relevant research on indoor air temperature disclosed an air change rate per hour of 10 ACH for different window-to-floor ratios. Accordingly, the expected decrease of the overheated hours was found to be between 36% and 42%, 37% and 39%, and 37% and 39% for sandcrete blocks, concrete and baked bricks, respectively [118] studied.

Another study on WWR and WFR indicated that the combination of these design criteria could be worth for further examination. This helps investigators to evaluate as well as determine the influences of these important elements in tropical climates.

6. Conclusion

In conclusion, the most important design parameter to manage thermal comfort is the building envelope. It is crucial because it affects the energy efficiency for high rise building in the hot–humid climate especially in Malaysia. This research study was conducted to examine the impact of thermal performance of the parameters in a building envelope on indoor air temperature in a typical residential building as shown in Table 4.

Studies have shown that a strong relationship exist between various building components such as shading devices, external wall, external roof and external glazing and insulation and the reduction of energy consumption as well as cooling in buildings. Furthermore, energy usage is also affected significantly by the shape of building such as length, width and height. Studies have also shown tremendous savings in energy consumption of high-rise buildings using passive design strategies as shown in Table 5.

In order to adopt passive design strategies effectively in hot and humid climatic conditions, it is important to consider the overall thermal performance of every building envelope components such as the optimal window to wall area, appropriate material for glazed windows and the right shading devices to accomplish thermal comfort when deciding on the building envelope so that dependence on mechanical systems are reduced.

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